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Pilot-Plant Studies of Slow-Rate Filtration

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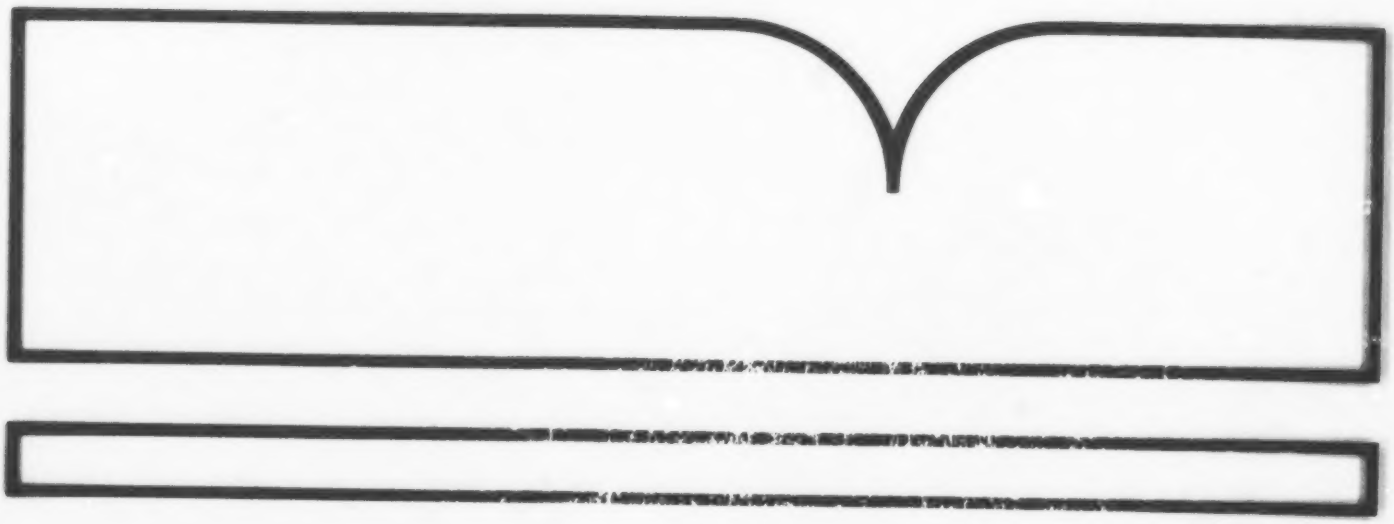

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16. ABSTRACT

Alternatives to conventional coagulation water filtration plants (those that utilize coagulation, flocculation, sedimentation and filtration) may be appropriate for some small water utilities. One such alternative is slow rate filtration. This paper describes pilot plant studies undertaken to evaluate slow rate filtration for the removal of particulates, total coliforms, standard plate count bacteria, and organics (TOC and THMFP). Two pilot-scale filtration systems were used: a slow sand filter (operated over 800 days), and a second slow sand filter operated in parallel with a slow rate filter containing granular activated carbon media (operated over 200 days). Results from both systems will be presented.

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Pilot-Plant Studies of Slow-Rate Filtration

Kim R. Fox, Richard J. Miltner, Gary S. Logsdon, Douglas L. Dicks, and Larry F. Drolet

Alternatives to conventional water filtration plants, which use coagulation, flocculation, sedimentation, and rapid filtration, may be appropriate for some small utilities. One such alternative is slow-rate filtration. This article describes pilot-plant studies that were undertaken to evaluate slow-rate filtration for the removal of particulates, total coliforms, standard plate count bacteria, and organics (total organic carbon and trihalomethane formation potential). Two pilot-scale filtration systems were used: a slow sand filter, operated for 800 days, and a second slow sand filter operated in parallel with a slow-rate filter containing granular activated carbon, operated for 200 days. Results are presented for both systems.

Although the concept of slow-rate filtration is not new, many questions still exist concerning its application and effectiveness. New analytical techniques, e.g., particle counting, improved turbidimetry, improved growth media for microbiological analysis, and advanced techniques for measuring organic constituents, allow for a more detailed study of filters than was possible in the early 1900s. The US Environmental Protection Agency's (USEPA's) Drinking Water Research Division (DWRD) recently examined slow-rate filtration on a pilot scale to evaluate its use by small water systems for the control of selected, regulated inorganic, microbiological, and organic drinking water contaminants.

This article describes two pilot-scale filtration systems: a slow sand filter, operated for 800 days, and a second slow sand filter in parallel with a slow-rate filter containing granular activated carbon (GAC), i.e., a slow carbon filter, operated for 200 days. The filters were operated at rates that reportedly allowed biological action to occur, e.g., 0.12 m/h.[1] Long contact time in a slow carbon filter may provide a long-term, cost-effective solution to organic or color control problems for small systems. The article discusses operating experiences and water treatment data for the two pilot filter systems and attempts to relate this information to the operation of slow-rate filters in small water systems.

TABLE 1
Characteristics of pilot-scale slow rate filters

Parameter	Sand Filter A	Sand Filter B	Activated Carbon Filter B
Inside dimension—m^2 (sq ft)	0.21 (2.25)	0.1 (1.09)	0.1 (1.09)
Media			
Type	Sand	Sand	12 × 40 GAC
Effective size—mm	0.17	0.29	0.55–0.65
Uniformity coefficient	2.1	1.8	1.6–2.1
Depth—m (in.)	0.76 (30)	0.82 (32)	0.82 (32)
Mean height of reservoir above media—m (ft)	1.25 (4.10)	1.09 (3.58)	1.09 (3.58)
Flow rate—m^3/d (gpd)	0.58 (152) 0.87 (228)*	0.29 (76)	0.29 (76)
Loading rate—m/h (gpm/sq ft)	0.12 (0.048) 0.18 (0.072)*	0.12 (0.048)	0.12 (0.048)
Mean detention time in reservoir—h	10.6 7.07*	9.21	9.21
Filter empty bed contact time—h	8.69 5.79*	6.87	6.87

*Flow rate was increased 50 percent at start of fifth cycle

Slow-rate filtration

Slow sand filtration originated in England in the early to middle 1800s.[2] Slow sand filters were first built in the United States in the late 1800s, and the process is still being used in some areas. The land requirements of slow sand filters and their unsuitability for treating high-turbidity surface waters led to a decline in their use by large municipalities. Small communities tended to follow the examples of the large municipalities and installed more sophisticated rapid sand filters. Although large areas of land would be required if slow-rate filters were used to treat water for a large city (Figure 1), only 21 m^2 of filter area would be required for a small community needing 100 m^3/d of drinking water. For small communities and other users of small amounts of water in areas where land is inexpensive, slow-rate filters offer substantial economic advantages, including lower capital and operating costs.[1]

During slow-rate filtration, water enters the reservoir above the filter media and is detained there for 3–12 h so that some sedimentation occurs. Some biological action also takes place in the reservoir.

Filtration is assisted by a thin layer

known as the schmutzdecke, which builds up on top of the media. As water enters the schmutzdecke, biological action breaks down some organic matter, and inert suspended particles may be physically strained out. The water then enters the top layer of sand where more physical straining and biological action occurs, as well as some attachment of particulates onto the sand grain surfaces. Also, some sedimentation occurs in the pores between the media grains.[1]

Because the operation of slow-rate filters is relatively simple, only moderate amounts of time are needed for daily maintenance, which entails checking flow rates and head loss, measuring filtered water turbidity levels, monitoring disinfection equipment, conducting miscellaneous sampling, and recording appropriate data.

When the schmutzdecke builds up to the point at which it clogs the top sand layer and causes head loss through the filter to reach a predetermined level, the filter must be drained and the top layer of sand removed. This period of scraping is the only time during normal operation that additional personnel may be required to operate the filter. The length of time between scrapings depends on how much material is filtered out of the water; high turbidity shortens the cycle.

Pilot plant

Pilot studies were conducted on two separate filtration systems. Filter A was housed in a box constructed of transparent thermoplastic with an inside area of 0.21 m^2 and contained 0.76 m of fine sand on top of torpedo sand, support gravel, and an underdrain system (Table 1). The underdrain system was designed for collecting the filtrate and for backfilling the filter after scraping (backwashing was not a design factor). The sand used was described by the supplier as a "clean builder's sand." It had an effective size of 0.17 mm and a uniformity coefficient of 2.1.

Filter system B was also housed in transparent thermoplastic but differed from filter A in that the filter box was divided in half, with one side of the filter containing sand and the other side containing granular activated carbon. Parallel 0.1-m^2 filters contained 0.82 m of media on top of support gravel and underdrains similar to those of filter A (Table 1). The sand was a graded mix of builder's sand and a sand commonly used for rapid sand filtration. This mix had an effective size of 0.29 mm and a uniformity coefficient of 1.8. A commonly available water-grade GAC (12 × 40 mesh coal base) with an effective size ranging from 0.55 to 0.65 mm was studied in the second half of the filter. Because this size is much larger than that typically used for slow-rate filtration media, particulate penetration was anticipated.

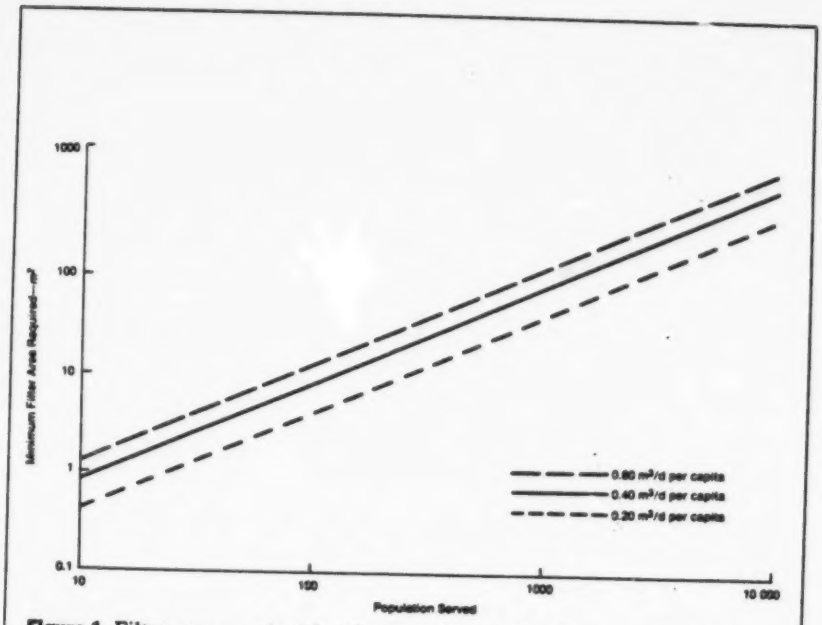

Figure 1. Filter area required for slow-rate filters *(filtration rate—0.2 m/h)*

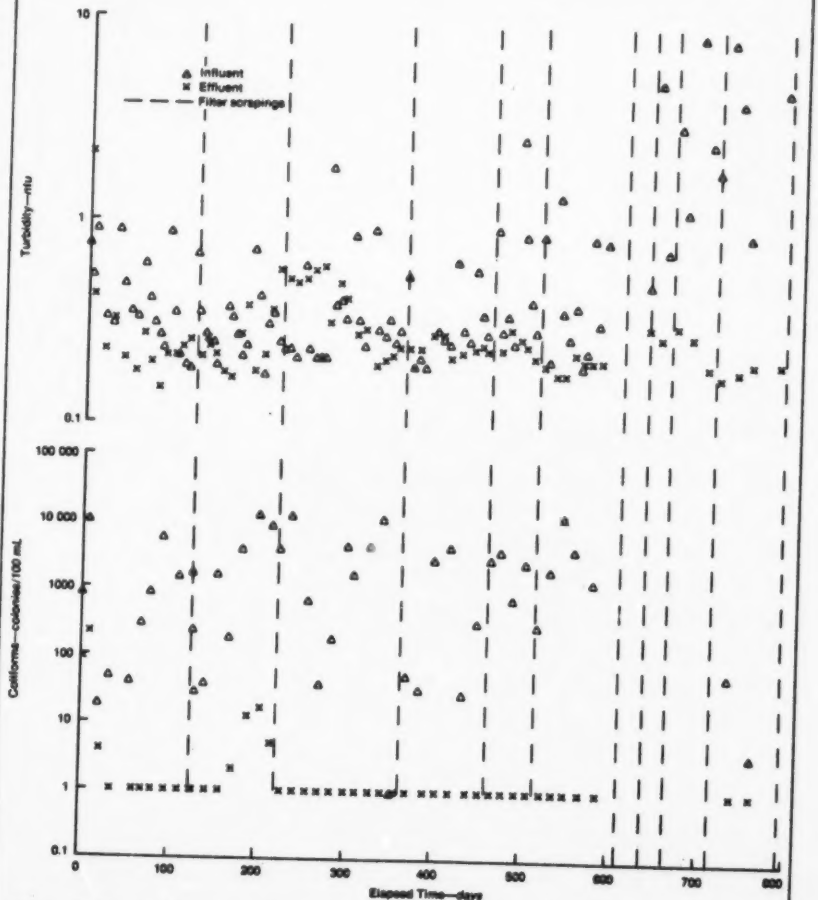

Figure 2. Turbidity and coliform removal by slow sand filter A *(coliform counts < 1 are plotted as 1)*

Several different water sources were used for this study. For the first six cycles (intervals between schmutzdecke scrapings), water for filter A was obtained from a local gravel pit lake—a low-turbidity surface water. Raw sewage was added to the source water in the storage tank to produce a high coliform level (a sewage-to-water volume ratio of 1:2500). For the last four cycles of the filters, when a higher turbidity was desired, Ohio River water was used. For a portion of the first cycle of filter B, low-turbidity water was obtained from a local reservoir. Because coliform identification was troublesome and turbidity was very low, Ohio River water was used for the remainder of the study.

The water was hauled by tank trailer to the pilot plant and stored in two separate tanks—one for each system. Since the storage tank for filter A was located inside the laboratory, the filter received water at a fairly constant temperature. Although the storage facility for filter B was located outside, the water traveled through approximately 150 m of tubing to reach the filter, and, thus, water entering filter B was also not subject to significant changes in temperature. Because of this long distance of travel, however, the turbidity of the water was lowered.

Flow from the storage tanks was controlled by solenoid valves so that the level of water in the reservoirs above the media varied no more than 2.5 cm for filter A and no more than 9 cm for filter B. (The parallel sides of filter B shared a common reservoir.) These reservoirs, in addition to allowing time for sedimentation, provided the head required to force water through the schmutzdecke, media, and miscellaneous plumbing on the effluent side of the filters. When the filters were clean, head loss through the media was low and valves were necessary to reduce the effluent flow rates to desired levels. As the head loss in the filter increased, the rate valves on the effluent streams were adjusted to maintain a constant flow rate.

Sampling ports of stainless steel tubing were placed horizontally at various depths in the media of each filter for profile sampling. The tubing had slots, approximately 1.0 mm wide, to allow for the collection of samples from near the wall to the middle of filter A and from wall to wall of each side of filter B. Samples from these ports were taken over a long period of time. When the ports were used for sampling, their flow rates were kept very low (2-3 mL/min) to avoid increasing significantly the flow through any part of the filter or disrupting the media. Initially, a small amount of sand entered the tubes, but no sand was observed in subsequent samples. The ports were also used for determining differential head loss.

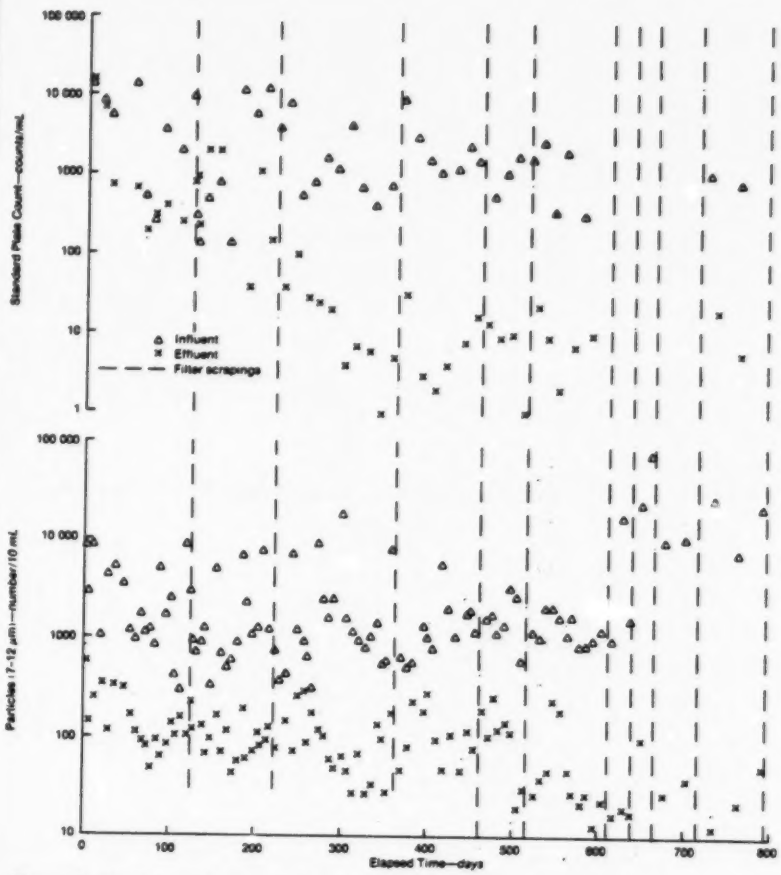

Figure 3. Particle and standard plate counts for slow sand filter A

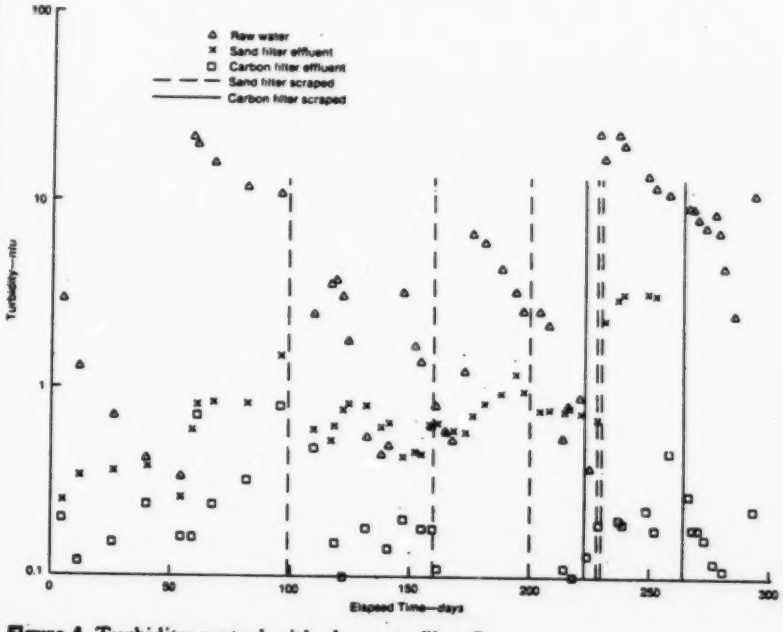

Figure 4. Turbidity control with slow-rate filter B

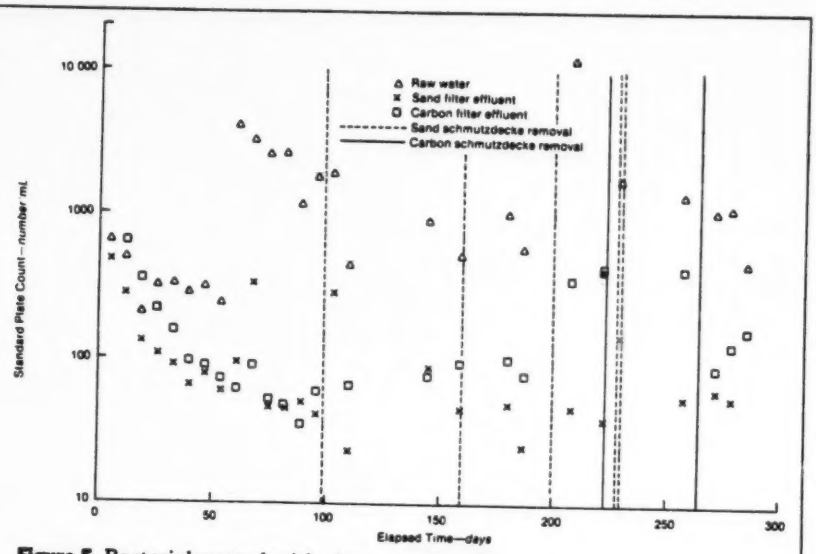

Figure 5. Bacterial control with slow-rate filter B

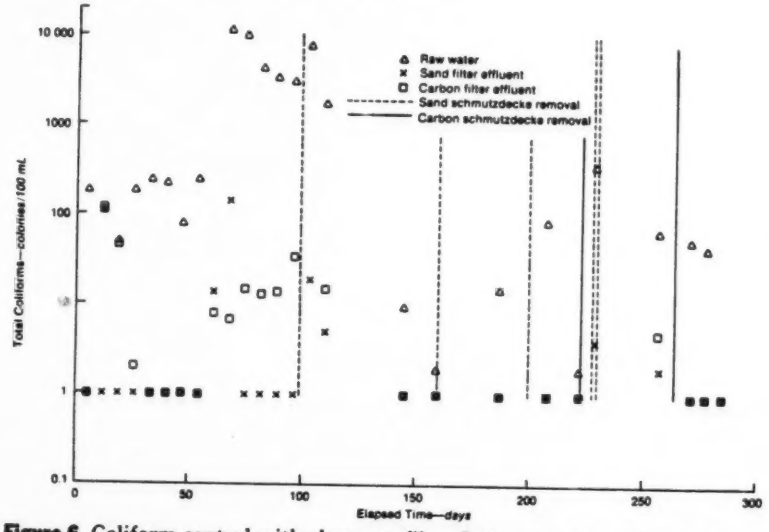

Figure 6. Coliform control with slow-rate filter B *(counts < 1 are plotted as 1)*

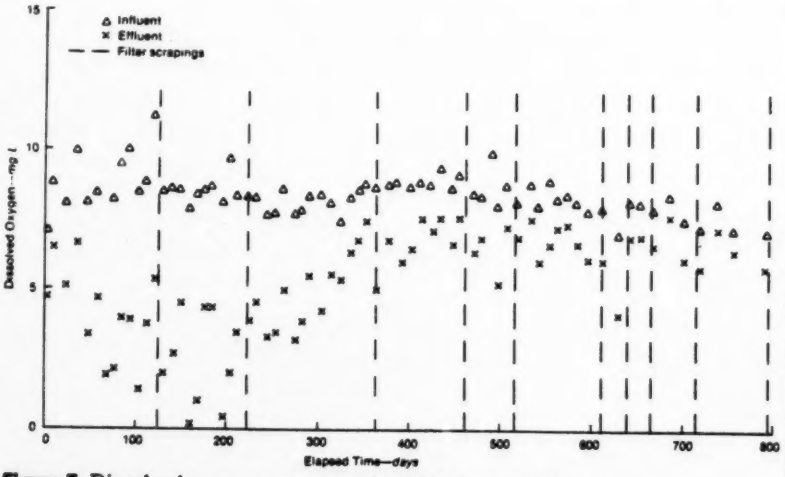

Figure 7. Dissolved oxygen concentrations for slow sand filter A

Short-circuiting of water along the filter walls was prevented by fastening 6-mm strips of transparent thermoplastic to the filter walls at two levels in the media. Both the media and the lower part of the reservoir were shielded from light to prevent algal growth. (Since larger filters would not have clear walls, this problem would not normally occur.)

Filters were scraped when flow rates could not be maintained. The influent to the reservoir was shut off, water levels were dropped to just below the schmutzdecke, and the schmutzdecke and some sand, or granular activated carbon, were removed. A typical scraping removed a depth of approximately 1 cm of media. Filtered water was then pumped into the effluent side, at a very low rate to avoid disrupting the media, until the media was under several centimetres of water. The reservoir was then slowly filled with raw water, and the filter put back in service. The typical scraping process took 8 h.

Pilot plant results

Particulate control. Turbidity levels in the influent to sand filter A ranged from 0.2 to 10 ntu. After the initial ripening period of the filter, its effluent turbidity levels were always less than the 1.0-ntu maximum contaminant level (MCL) and were routinely less than 0.35 ntu during the last half of the study (Figure 2). Effluent samples taken after scraping the schmutzdecke did not show any significant turbidity increases. Even after the fourth filter scraping, when the flow rate was increased by 50 percent, no increase in effluent turbidity levels was observed.

Turbidity reduction was also evident in the particle count data. A particle counter* capable of quantifying size and distribution of particles in the range of 2.5 to 150-μm diameter in an aqueous sample was used to analyze both the influent and effluent. Sand filter A displayed one to two log reductions of *Giardia*-cyst-sized (7-12 μm) particles and tended to show greater reductions as the filter became clogged (Figure 3). Counts of other particle sizes exhibited similar reductions. Profile sampling showed only minor reductions in particle counts below the top 7 cm of sand.

After seven weeks of treating reservoir water, filter B was switched to treating Ohio River water that had a turbidity of 0.4-23 ntu. This, coupled with the larger effective size of sand filter B media, resulted in poorer turbidity control than that observed for filter A (Figure 4). Throughout the study, effluent turbidity levels gradually increased as filter B became clogged. After five cycles, the

*HIAC Particle Size Analyzer, Model PC-320, CMH-150, Pacific Scientific Co., Montclair, Calif. (Mention of commercial products does not imply endorsement by USEPA.)

filter was ineffective for maintenance of a 1-ntu MCL. Turbidity profiles developed during cycle 6, prior to taking the filter out of service, showed a turbidity of ≥1.0 ntu at each depth sampled. The effect of excessive turbidity loading on sand filter B is also seen in Table 2. Cycle length decreased and startup head loss increased as the mean effluent turbidity increased with successive cycles. Clearly, the filter had become clogged. Even a 5-cm scraping that returned the filter to low head loss at the start of cycle 6 was short-lived (Table 2). In areas with high raw water turbidities, presedimentation may be necessary prior to slow-rate filtration. Pilot testing of the water to be treated would show whether filter clogging would be excessive.

For the period studied, granular activated carbon filter B, with a large effective size (0.6 mm), provided better turbidity control than sand filter B (Figure 4). Effluent turbidities were typically <0.5 ntu and often <0.1 ntu. The interval between scrapings was longer for the carbon filter than for either sand filter. (The scraping at 260 days was not because of loss of flow rate but because short-circuiting and formation of air pockets along the walls in the upper 10 cm required correction.)

Bacterial control. Samples analyzed for total coliform and standard plate count bacteria were collected routinely from sand filter A. Data showed excellent bacterial removal (Table 3; Figures 2 and 3), and after filter ripening, four to five log reductions in total coliform densities were routinely achieved. With the exception of one three-week period and one isolated sample, coliform densities in effluent samples were <1/100 mL. Standard plate counts showed that sand filter A lowered bacterial counts, but the data during the first 250 days were erratic (Figure 3). When effluent vinyl tubing was replaced with stainless steel, effluent standard plate counts were lower and more consistent. Data for particulates in the 7–12-μm size range (Figure 3) suggest effective control of *Giardia* cysts.

Bacterial control by filter B is shown in Figures 5 and 6. Following high counts at startup, one to two log reductions in standard plate counts were observed with both sand and activated carbon filtration. One to three log reductions in coliform densities were typically observed for both filters. Comparison of filters A and B showed that bacterial control improved as the effective size of the sand decreased. This was observed earlier by Hazen.[3]

Dissolved oxygen. Dissolved oxygen was monitored to ensure that sufficient oxygen was available for biological action. Circulation of the source water in the storage tanks provided high oxygen levels in the raw water. Oxygen in

TABLE 2
*Operation of slow sand filter B**

Cycle	Head Loss at Start of Cycle *cm*	Head Loss at End of Cycle *cm*	Cycle Length *days*	Mean Turbidity—*ntu*		Depth Removed During Scraping *cm*
				Influent	Effluent	
1	1	44	98	7.6	0.59	1.0
2	3	43	62	2.4	0.63	1.0
3	6	38	40	2.7	0.73	1.0
4	10	39	28	4.5	0.77	1.0
5	24	41	6	16	2.4	5.0
6	2.5	38	16†	16	3.1	†

*Effective size of media—0.29 mm; filtration rate—0.12 m/h (0.048 gpm/sq ft)
†Filter taken out of service

TABLE 3
Coliform removal by slow sand filter A

Run	Run Length *days*	Coliforms in Influent *colonies/100 mL*		Coliforms in Effluent*	
		Range	Geometric Mean	Total Number of Samples	Number of Samples Exceeding 1 colony/100 mL
1†	40	1-10 100	257	12	12
1	85	1-8 100	304	24	0
2	97	1-25 400	383	33	8
3	141	1-22 900	795	41	0
4	98	1-12 000	321	25	0
5	55	1-5 450	593	15	0
6	100	300-15 000	4060	19	1
7	26	‡	‡	‡	‡
8	28	‡	‡	‡	‡
9	50	‡	‡	‡	‡
10	71	1-60	5.8	6	0

*No disinfectant used in these filter runs
†Filter ripening period for new sand
‡Not applicable—no samples taken

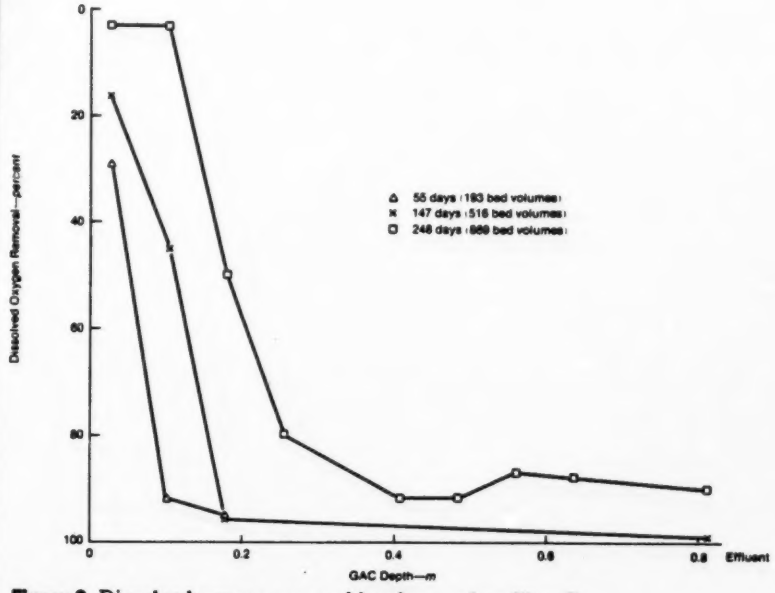

Figure 8. Dissolved oxygen removal by slow carbon filter B

TABLE 4
Organics control by slow sand filtration

Parameter	Filter A	Filter B
Effective size of sand—*mm*	0.17	0.29
TOC in influent—*mg/L*	7.1-11.1	1.5-3.2
TOC removal—*percent*		
Mean	19	15
Range	8-31	5-24
THMFP* in influent—*μg/L*	124-322	84-150
THMFP removal—*percent*		
Mean	18	15
Range	3-34	8-24

*Seven-day storage; 15 mg chlorine/L added; pH—6.6-7.1; temperature—20°C

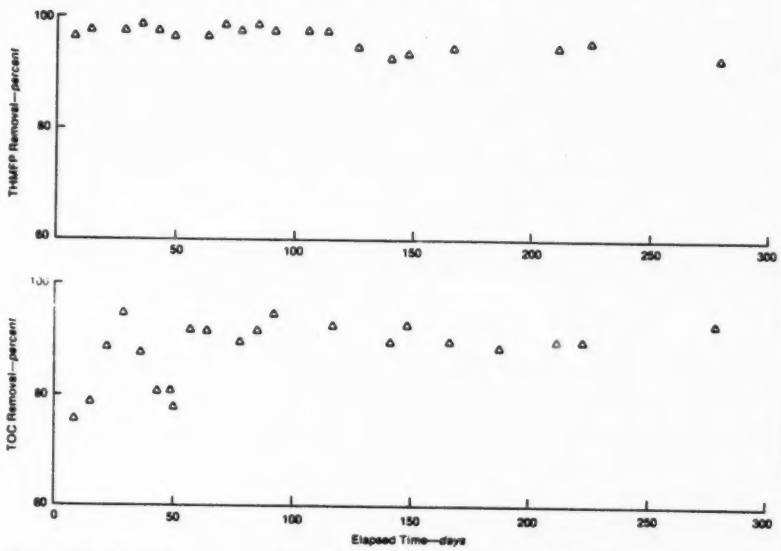

Figure 9. Organics control by slow carbon filter B *(influent—84-150 μg THMFP/L; 1.5-3.2 mg TOC/L)*

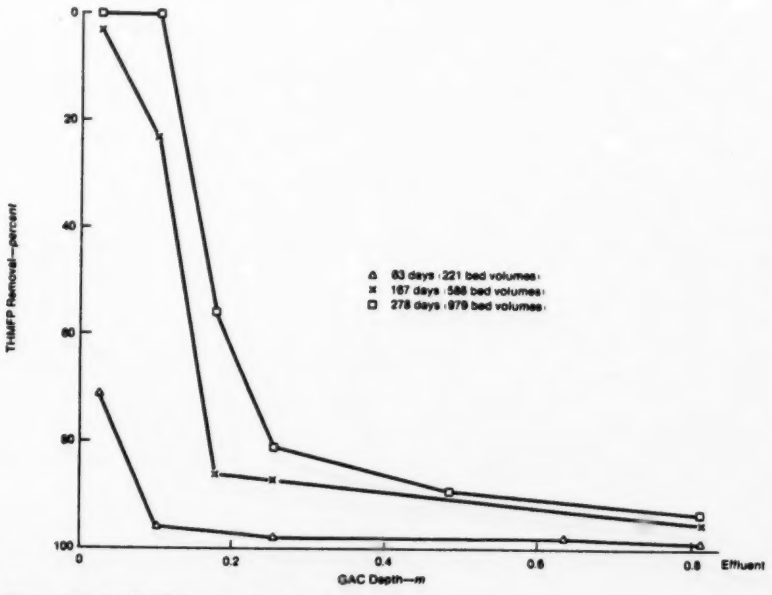

Figure 10. THMFP control with slow carbon filter B

effluent samples taken from filter A (Figure 7) and from sand filter B was measured. Profile samples showed that oxygen consumption occurred in the top layer of sand filter A. This finding tends to support the concept of intense biological action in the upper layer of the filter media. The mean dissolved oxygen level in the influent to sand filter B was 7.85 mg/L, whereas the mean effluent level was 7.33 mg/L.

Dissolved oxygen removal by activated carbon filter B was observed to be time-dependent. Dissolved oxygen levels in filter B effluent ranged from <0.2 to 0.6 mg/L. Since profile sampling demonstrated a dissolved oxygen wavefront movement through the adsorbent, a poorly oxygenated effluent would be expected over a long period of time (Figure 8). However, bacteria enumerated by standard plate count were observed in the effluent from this low-dissolved-oxygen environment (Figure 5), suggesting that aerobic organisms had survived passage through the media.

Organics control. During the first two cycles, filter A was examined for its control of total organic carbon (TOC) and seven-day trihalomethane formation potential (THMFP). As shown in Table 4, removals averaged 19 and 18 percent, respectively.

Because the TOC of the gravel-pit water was relatively high (7.1-11.1 mg/L) a capillary column, gas chromatographic profile was conducted. Compared with typical surface water profiles,[4] the water was heavily laden with low- to medium-molecular-weight organic compounds. This was attributed to an oil dump near the gravel pit. For this reason, gravel-pit water was not treated in filter B. The reservoir water influent and, later, the Ohio River water influent to filter B had lower TOC values (1.5-3.2 mg/L). When treating these waters, sand filter B averaged 15 percent removal of both TOC and seven-day THMFP. On a percentage removal basis, the two sand filters behaved similarly, but on a weight removal basis, filter A was more effective.

Control of organics by activated carbon filter B was very effective but, as expected, was dependent on time. Figure 9 shows mean TOC and seven-day THMFP removals of 88 and 97 percent, respectively. Periodic profile sampling showed a time-dependent wavefront movement of organics through the adsorbent, which is seen in Figure 10 for seven-day THMFP. Similar behavior was observed for TOC concentrations.

Discussion

Sand filtration. Slow sand filtration can be effective for turbidity, particulate, and bacterial control. Postchlorination can further reduce the bacterial densities of filter effluent. In these pilot-scale

studies, turbidity removal and bacterial control were generally better for filter A, which used a smaller, 0.17-mm-effective-size sand, than for filter B, which used a larger, 0.29-mm-effective-size sand. Filter A, treating a relatively low turbidity water (0.2–10 ntu), operated effectively for more than 800 days, whereas filter B, treating a higher turbidity water (0.4–23 ntu) at the same loading rate, became clogged with particulates and ineffective after 230 days of service. This is typical of problems encountered where slow sand filters were used to treat turbid waters. When questions exist about the suitability of raw water for treatment by slow sand filtration, a pilot-plant investigation should be undertaken to verify treatability before a slow sand filter plant is built.

At startup, about 30 days were required to bring particulate and bacterial counts of the effluent down to a consistent level. This ripening period, when the filters slowly establish an active biological zone, may have been long because of the time needed to flush material off new media. In these pilot-scale studies, no problems were observed following schmutzdecke scraping, effluent quality being excellent soon after the filters were restarted. These pilot filters were drained to just below the schmutzdecke, and no load was applied to the media during scraping. It is conceivable that a full-scale filter might take more time to recover, because it is more severely stressed during scraping when water is drained from the media and the sand surface is subjected to motions emanating from shoveling, walking, moving wheelbarrows, and, perhaps, mechanical media-cleaning equipment.

The slow sand filters were observed to remove an average 15–19 percent of influent TOC and THMFP. Sand filter A was more effective on a weight removal basis for organics control than sand filter B. In addition to differences in influent organics loading (Table 4), this difference in effectiveness might be attributable to sand filter B's larger effective size, which resulted in the passing of more particulates and, therefore, more particulate-adsorbed organics, or to a difference in biodegradability of the oil-laden influent to sand filter A. The 15–19 percent control of organics is poorer than the 25–50 percent typically seen in conventional treatment (coagulation, sedimentation, and rapid sand filtration).[5] A possible explanation for the performance of coagulation-filtration plants is their better removal of fine particulates that adsorb organics. Another explanation is that coagulation removes humic and fulvic substances that are THM precursors. If these substances can survive for a long time in natural waters, they are probably not a good source of food for microorganisms and thus would not be removed by the biota in the slow sand filter. Thus, a small system with a raw water containing high THMFP levels may not find slow sand filtration suitable for controlling THMs.

GAC filtration. Using a readily available 12 × 40-mesh GAC in a slow-rate filtration mode that allowed several hours of contact time provided excellent organics control and better turbidity control than its large effective size would have suggested.[3] Without a disinfectant, with nutrient concentration by adsorption, and with reduced dissolved oxygen concentration in the lower depths of the media, bacterial control was effective. As with slow sand filtration, postchlorination would provide a second barrier to bacteria in the filter effluent. During these studies, no odor from the activated carbon filter was detected in the effluent, even though the water approached anaerobic conditions. Under full-scale operating conditions, reaeration may be required to ensure a finished water of acceptable quality.

Although the slow sand filtration process may not provide sufficient treatment for small utilities that have problems with THMs or other organics, slow activated carbon filtration may provide the required control. Additional study of slow activated carbon filtration of waters of varying quality is needed to assess its cost and compare it with other processes for organics control. Assuming a water with a THMFP content similar to that of the influent to filter B and a THMFP movement through the carbon similar to that observed in filter B, GAC replacement costs would be approximately $1.20/3785 L (1000 gal), depending on the concentration of total trihalomethanes (TTHMs) formed in the distribution system following postchlorination. For small water utilities with TTHM problems, such GAC costs may be acceptable.

Summary

Studies performed early in this century demonstrated effective particulate and bacterial control by slow sand filtration.[3] Using current analytical techniques, i.e., particle counting, improved turbidimetry, and improved growth media for bacterial analysis, the pilot-scale studies described in this article demonstrated similar bacterial control. Modern analytical techniques have also permitted investigation of organics control by slow sand filtration.

These pilot-scale studies indicate that slow-rate filtration can be a relatively easily operated and effective process for small systems currently confronted with noncompliance with drinking water standards or for new small systems.

The Drinking Water Research Division of USEPA anticipates further study of these pilot-scale filters. Possible investigations include parallel studies of different effective sizes of sand for organics control of the same water, parallel studies of different effective sizes of the same activated carbon for particulate and organics control of the same water, parallel studies of organics control by activated carbon or sand capped with activated carbon for waters of varying quality, investigation of effluent water quality problems found after the media is replaced, studies of *Giardia* cyst and virus removal, and cost-effectiveness analyses of the slow-rate filtration process.

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References

1. HUISMAN, C. & WOOD, W.E. *Slow Sand Filtration*. WHO, Geneva (1974).
2. *The Quest for Pure Water*. AWWA, Denver, Colo. (1981).
3. HAZEN, A. *The Filtration of Public Water Supplies*. John Wiley & Sons, New York (3rd ed., 1913).
4. STEVENS, A.A. ET AL. Gas Chromatographic Techniques for Controlling Organic Removal Processes. *Jour. AWWA*, 73:10:548 (Oct. 1981).
5. SYMONS, J.M. ET AL. Treatment Techniques for Controlling Trihalomethanes in Drinking Water. USEPA, DWRD, Cincinnati, Ohio (Sept. 1981).

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